

Do dwarf spheroidal galaxies contain dark matter?

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ABSTRACT

The amount of dark matter in the four galactic dwarf spheroidals with large mass-to-light ratios is investigated. Sextans has a cut-off radius which is equal to the expected tidal radius, assuming a high mass-to-light ratio. This satellite very likely is dark matter dominated. Carina, Ursa Minor and Draco, on the other hand, cannot contain a dominating dark matter component if the observed 'extra-tidal' stars are located exterior to the tidal radii of these systems. The evidence for tidal stripping in the absence of dark matter is also supported by the fact that the observed cut-off radii of all three satellites are equal to their tidal radii, assuming a low, globular cluster like mass-to-light ratio. The large velocity dispersions of these galaxies, on the other hand, provide strong evidence for a massive dark matter component. In this case, the 'extra-tidal' stars lie deeply embedded in the dark matter potential wells of the satellites. These stars then would represent a gravitationally bound, extended stellar component with unknown origin.

Subject headings: dark matter — Galaxy: formation — Local Group

1. Introduction

Nine dwarf spheroidal galaxies (dSphs) are known to orbit the Milky Way. Like globular clusters, the dSphs have low luminosities, of order $10^5 - 10^7 L_{\odot}$. Their core radii are however typically an order of magnitude larger than in globular clusters, leading to very low surface brightnesses (see the review by Gallagher & Wyse 1994). As a result, the Milky Way’s massive dark halo exerts a strong tidal force on these objects, which ultimately might lead to their disruption. Indeed, at least one of them, Sagittarius (Ibata et al. 1994, Mateo et al. 1995), is known to be currently torn apart.

Recent theoretical and observational work has focussed on the dark matter content in dSphs. This question is very interesting because of two reasons. First, a detailed investigation of the dark halo structure in these nearest galaxies could provide important information on the formation of dark matter halos and on the nature of dark matter. Second, the origin and future fate of dSphs within the tidal field of the Galaxy is strongly coupled with the question of their dark matter content.

The origin of the galactic dSphs is probably closely related to the formation history of the Milky Way. Cosmological models of hierarchical structure formation in a cold dark matter scenario naturally produce satellite systems around massive galaxies, which represent those galactic building blocks that manage to escape merging and remain gravitationally bound for a Hubble time. In this case, we would expect that dSphs, like other galaxies, contain a dark matter halo. Another possibility has been suggested by Lynden-Bell (1982), who noted that the dSphs and the Magellanic Clouds are not uniformly located on the sky, but occupy two great circles. They therefore might represent the debris of two massive, tidally disrupted progenitor satellites. As noted by Barnes & Hernquist (1992), dwarf galaxies could indeed form inside tidal arms during galaxy-galaxy collisions. These systems however do not contain significant amounts of dark matter.

An answer to the dark matter question might be given by observations of the stellar velocity dispersions in dSphs, which would provide an estimate of their virial mass. From this, a mass-to-light ratio M/L can be derived. The observational uncertainties in the central velocity dispersions of the dSphs are still very large. It is however clear that most dSphs have M/L values that are much larger than in globular clusters. The four galaxies with exceptionally high M/L values and galactocentric distances smaller than 100 kpc are Carina, Draco, Sextans and Ursa Minor (table 1). These systems seem to contain large amounts of dark matter within their visible radius.

This conclusion has been questioned by Kuhn & Miller (1989; though see Pryor 1996), who argued that a resonance of the tidal force with collective oscillation modes of a dSph could significantly heat the stellar system, resulting in large velocity dispersions and large apparent mass-to-light ratios, even without a dark matter component. As a result of this interaction, the system expands beyond its tidal radius, particles are lost and the dSph eventually dissolves. As Kuhn & Miller (1989) note, without a dark matter component the dSphs with high apparent M/L and large central velocity dispersions would be gravitationally unbound even in the core regions and should disperse on a free expansion timescale τ_{dyn} , which is of order $10^8 - 10^9$ yrs. Kuhn (1993) made however the interesting point that the lifetimes of not internally bound satellites could actually be much longer than τ_{dyn} . The details are complex and depend on the initial velocity distribution of the particles. Systems with a small velocity dispersion along the line connecting the dSph and the galactic center and with a large dispersion tangential to this will disperse on timescales smaller than τ_{dyn} . Configurations with the reverse dissolve more slowly than expected from free expansion. If the timescales for disruption become long enough, a large fraction of the dSphs could actually be unbound but not yet dispersed. Then the large velocity dispersions, observed in the four galactic dSphs are no direct signature for dark matter.

Kuhn & Miller (1989) studied the response of a stellar system to an external, oscillating tidal field, neglecting coriolis terms. Oh et al. (1995) published detailed numerical computations of the tidal disruption of dSph satellites in a realistic, logarithmic Galactic potential, taking into account coriolis forces. They started with isotropic King profiles (King 1966) and initial cutoff radii, r_k , equal to or larger than the tidal radii at perigalacticon (King 1962). The tidal radius for a logarithmic Galactic potential is (Oh et al. 1992)

$$r_t = a \left(\frac{M_{dSph}}{M_G} \right)^{1/3} \left(\frac{(1-e)^2}{[(1+e)^2/2e] \ln[(1+e)/(1-e)] + 1} \right)^{1/3}, \quad (1)$$

where e and a are the orbital eccentricity and the semi-major axis, respectively. M_{dSph} and M_G are the mass of the dSph and of the Galaxy inside a , respectively. In contradiction to Kuhn (1993), Oh et al. find that the unbound but not yet dispersed systems have velocity dispersions which are comparable to the virial equilibrium value prior to disruption. This leads to the conclusion that the four galactic dSphs with observed large velocity dispersions must contain dark matter, irrespectively of whether the systems are in virial equilibrium or are being tidally disrupted. Very strong tidal interactions of dSphs with the Milky Way, leading to their disruption, have also been studied by Piatek & Pryor (1995), but they note that their simulations are not relevant to the Kuhn & Miller (1989) picture.

This theoretical controversy about the origin of the high velocity dispersions in dSphs has led to confusion in interpreting the observations. For example, Bellazzini et al. (1996) have investigated the correlation of structural properties of dSphs with their galactocentric distances (see also Djorgovski & de Carvalho 1990, Mateo et al. 1993, Caldwell et al. 1992). Following the model of Kuhn & Miller (1989), they conclude that the high velocity dispersions observed in some dSphs are of tidal origin and that the amount of dark matter is probably overestimated. In contrast, Irwin & Hatzidimitriou (1995) present new observations on the morphology of dSphs. They find a component of 'extra-tidal' stars

which they interpret as an evidence for tidal disruption. Following Oh et al. (1995), Irwin & Hatzidimitriou conclude that all the dSphs with large M/L contain significant amounts of dark matter.

Given this situation, it is very important to find more arguments for or against dark matter in dSphs. This *Letter* will combine recent detailed observations on the morphology of dSphs with recently published, detailed numerical calculations. In section 2 it is shown that Draco, Ursa Minor and Carina cannot contain a dominating dark matter component, if the interpretation by Irwin & Hatzidimitriou of a detected 'extra-tidal' component is correct. Sextans however might contain significant amounts of dark matter and an 'extra-tidal' component. A discussion follows in section 3.

2. The dark matter content derived from an extra-tidal stellar component.

Irwin & Hatzidimitriou (1995) have presented a new determination of the structural parameters for the four dSphs with exceptionally large M/L (table 1). With the exception of Sextans, the major axis surface brightness profiles can be well fitted by one-component King profiles with concentration $c = 0.5$, leading to an accurate determination of the cut-off radii r_k . In addition, beyond r_k an excess of so called 'extra-tidal' stars is found, which, according to Irwin & Hatzidimitriou (1995) indicates ongoing tidal stripping. Indeed, the simulations of Oh et al. (1995) lead to an extended (extra-tidal) component if the system has a cut-off radius which is larger than its tidal radius r_t . The cut-off radii of the observed dSphs therefore cannot be smaller than their tidal radii ($r_k > r_t$). The N-body calculations by Oh et al. also show that the dSphs can only survive the tidal interaction for several Gyrs if r_k is smaller than twice the tidal radius ($r_k < 2 \times r_t$). This constraint probably applies to the present sample of dSphs, as it would be very unlikely that 50% of all galactic satellites will tidally disrupt and disappear within the next Gyr. In this case, the observed cut-off

radii provide an estimate of the tidal radii:

$$0.5 \, r_k < r_t < r_k. \quad (2)$$

Sextans is the exception. Its surface brightness profile can be fitted better by an exponential law or by a King profile with larger concentration: $c = 1$, resembling typical low-mass dwarf galaxies (Sandage et al. 1985). Evidence for extra-tidal stars associated with Sextans has been detected by Gould et al. (1992). However, the Gould et al. stars, associated with Sextans, are located within the tidal radius determined by Irwin & Hatzidimitriou (1995). They therefore are no longer clearly extra-tidal. If Sextans is gravitationally bound, we can use again the cut-off radius of the best fitting King profile as an estimate for r_t .

The tidal radius is determined by the orbital parameters of the dSphs. Due to uncertainties in the orbital eccentricity e , we consider both circular ($e = 0$) and eccentric ($e=0.5$) orbits. Following Bellazzini et al. (1996), we assume that the presently observed galactocentric radius d provides an estimate of the orbital semi-major axis. The dSphs orbit in the outer galactic regions, where it is reasonable to adopt a spherically symmetric galactic potential. We assume this to be logarithmic, corresponding to a dark matter mass distribution of

$$M_G(r) = \frac{v_c^2 r}{G} \approx 1.1 \times 10^{10} \left(\frac{r}{kpc} \right) M_\odot, \quad (3)$$

where G is the gravitational constant and $v_c \approx 220$ km/s is the constant circular velocity. Within the range of semi-major axes adopted for the present sample of dSphs, equation 3 should be accurate to within a factor of 2 (Da Costa et al. 1991). This uncertainty leads to errors in determining the tidal radii of less than a factor 1.3, which is small compared to

the uncertainties in the structural parameters.

Assuming $r_t \approx r_k$ (equation 2), we can rewrite equation 1 as follows

$$\rho_G(d) = \frac{3M_G(d)}{4\pi d^3} = \frac{3\left(\frac{M}{L}\right)L}{4\pi r_k^3} f(e) = \rho_{dSph}. \quad (4)$$

Here f is a function of the orbital eccentricity e and varies between $f(0) = 1$ and $f(0.5) = 0.42$. Only the left hand side of equation 4 (ρ_G) depends on the assumed galactic mass distribution. The right-hand side (ρ_{dSph}) is determined by the observed properties of the dSphs (table 1). Equation 4 expresses the fact that the mean mass density of a satellite within its tidal radius is equal to the mean galactic mass density within the average orbital radius.

The solid line in Figure 1 shows the average galactic mass density $\rho_G(d)$, calculated using equations 3 and 4. The open circles show ρ_{dSph} for the present sample of dSphs, assuming $M/L = 1$. The filled circles show ρ_{dSph} assuming a M/L value derived dynamically from the observed velocity dispersions (table 1).

If the extended stellar component in the dSphs is extra-tidal, the cut-off radii should provide a good estimate of the tidal radii (equation 2). The data points then should lie on the solid line. Even with the large error bars, which are due to the large observational uncertainties in the orbital and structural parameters, figure 1 clearly demonstrates that in this case Carina, Draco and Ursa Minor could not be dark matter dominated (see also Moore 1996). If their masses were as high as suggested from their velocity dispersions, their internal densities (filled circles) would be much larger than expected for a tidally limited satellite. No 'extra-tidal' stars should be observed as $r_t \gg r_k$.

Sextans has a cut-off radius which is consistent with the assumption of a large M/L . The good agreement of its kinematically derived average density (filled circle) with the

expected value provides strong support for the conclusion that this satellite is dominated by dark matter. If Sextans is a gravitationally bound satellite, then it must contain a dark matter halo as otherwise its tidal radius would be a factor of five smaller than its cut-off radius. The numerical simulations by Oh et al. (1995) then would indicate (see equation 2) that Sextans should completely disrupt within the next 10^8 yrs. It is very unlikely that we observe this satellite in such a short-lived evolutionary state. In addition, in this case Sextans should have higher ellipticities than observed.

3. Discussion

The solid line in figure 1 subdivides the diagram into two regions. Only those satellites which lie below this line should be tidally affected. The existence of 'extra-tidal' stars in Carina, Draco and Ursa Minor therefore would demonstrate that these dSphs cannot contain significant amounts of dark matter. Note that this conclusion is independent of the accuracy by which the velocity dispersion is determined. Any value of M/L which is larger than 3 would lead to such high internal densities that the cut-off radii could not be of order the tidal radii (Pryor 1996). If Sextans is not in the process of complete tidal disruption it must contain a dominating dark matter component. Such a difference in the dark matter content of the galactic satellites could result from different formation histories. It is intriguing that Carina, Draco and Ursa Minor lie in the Magellanic plane and might originate from a tidally disrupted progenitor satellite, as suggested by Lynden-Bell (1982). In this case, no significant dark matter component should indeed be found. In contrast, Sextans cannot be associated with the Magellanic plane (Lynden-Bell 1993). This object might represent a typical low-mass, low-surface density dwarf galaxy which was captured and still contains at least the inner parts of its original dark matter halo.

Up to now we have assumed that there exists an 'extra-tidal' stellar component.

However, the previous results seem to be in conflict with the observed high velocity dispersions in Carina, Ursa Minor and Sextans. The computations by Oh et al. (1995) demonstrate that, without dark matter, the velocity dispersion could not be as high as observed, even if tidal heating is taken into account. High dispersions might be measured in systems which are contaminated by close binary stars (Suntzeff et al. 1993). However, Armandroff et al. (1995) have shown that this effect can be ruled out in the case of the dwarf spheroidals. The most reasonable explanation seems to be that all four dwarf spheroidals contain massive dark matter halos. With the exception of Sextans, the extended stellar component then should not be classified as 'extra-tidal', because it actually lies deeply embedded in the potential well of the dwarf spheroidal's dark matter halos. How such an extended component could arise is unknown. One also might wonder about the puzzling coincidence that the observed cut-off radii of these dwarf spheroidals are very similar to the expected tidal radii, assuming no dark matter component.

More detailed observations and accurate velocity measurements of the extended stellar component are required in order to clarify whether there really exists a break to a shallower slope in the density profiles of the dwarf spheroidals and whether the outermost stars are tidally stripped. Such observations will also clarify the important question whether the dwarf spheroidals contain a dominant dark matter component or not.

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Name	$L(L_{\odot})$	$d(kpc)$	r_k (pc)	$\frac{M}{L} \left(\frac{M_{\odot}}{L_{\odot}} \right)$
Carina	$(2.4 \pm 1.0) \times 10^5$	85 ± 5	581 ± 86	59 ± 47
Draco	$(1.8 \pm 0.8) \times 10^5$	72 ± 3	498 ± 47	245 ± 155
Ursa Minor	$(2.0 \pm 0.9) \times 10^5$	64 ± 5	628 ± 74	95 ± 43
Sextans	$(4.1 \pm 1.9) \times 10^5$	83 ± 9	3102 ± 1028	107 ± 72

Table 1: The sample of galactic dSphs with large M/L . The physical properties are adopted from Irwin & Hatzidimitrou (1995), with L the total luminosity, d the galactocentric distance, r_k the cut-off radius and M/L the dynamically derived mass-to-light ratio.

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Figure 1 The solid line shows the average galactic mass density ρ_G (equation 3) as a function of galactocentric distance d . The open circles show the average internal densities ρ_{dSph} (equation 3) of the dSphs for $M/L = 1$. The filled circles show ρ_{dSph} , adopting the kinematically derived M/L (table 1). Error bars show the effect of the uncertainties in the galactocentric distance, orbital eccentricity, tidal radius and luminosity. In sequence of increasing d , the pairs of open and filled circles correspond to Ursa Minor, Draco, Sextans and Carina. dispersion $\sigma_r(r)$ and the dashed line shows the tangential velocity dispersion $\sigma_t(r)$.

